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QSI Response of Foam–Filled Composite Marine Sandwich Hull Panels: Simulation and Experiment

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Abstract

The response of certifiable advanced marine grade hybrid composite sandwich hull panels due to quasi–static indentation (QSI) by a 12.7mm diameter hemispherical indentor is investigated by means of experiments and finite element (FE) models. Techniques used to model the composite skins and the foam–core of the hull panels are described. The validity of the FE model to simulate the QSI response of three other different certifiable hull panels in simply–supported and rigidly–backed configurations is assessed. The inclusion of a plain woven–roving sheet of E–glass fibre in the composite skins is found to improve the degradation factor employed in an instant stiffness degradation material model. A rigidly–backed configuration is found to decrease the degradation factor.

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Keywords: composite sandwich; impact damage; marine; quasi–static indentation; finite element analysis.

1. Introduction

Quasi–static indentation (QSI) of foam–filled laminated composite marine sandwich hull panels is characterised in terms of the resultant indentation contact force between the indentor and the sandwich panel as the level of indentation or indentation displacement is varied. The force–indentation displacement history curve provides useful information regarding the amount of energy that can be absorbed by the hull panels at any instantaneous indentation displacement during a QSI event. The initial kinetic energy of the indentor is absorbed as mainly strain energy in the panel and dissipated through various modes of damage mechanisms in the skins and fracture in the core to maintain

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equilibrium of forces. The amount of energy absorbed by the hull panels subjected to QSI conditions at any instantaneous displacement depends on the geometrical features, such as thickness, and material properties of the constituent structures of the composite sandwich panel, the geometry of the indentor and the support configuration, amongst others. Whilst damage is not always easily detected by non–destructive visual inspection, the influence of Barely Visible Impact Damage (BVID) can have detrimental effects on the residual material properties of the hull panels after impact. In some cases, BVID is reported to decrease the residual strength of a composite sandwich panel by 50% [1]. Destructive inspection of composite hull panels is not always technically or economically feasible. Consequently, engineers tend to use a very low allowable strain limit, thereby hindering the exploitation of the high stiffness–to–weight benefit commonly associated with composite sandwich panels [2].

The finite element (FE) method is an attractive engineering tool to determine and investigate the response of hull panels subjected to different QSI conditions. Results obtained from the FE model combined with observations made from experimental testing improves the understating of the QSI response of hull panels.

In this investigation, an efficient FE model capable of simulating the QSI response of a foam–filled marine grade sandwich hull panel due to a hemispherical indentor in a simply–supported configuration is presented. The validity of the FE model to simulate the QSI response of other simply–supported and rigidly–backed sandwich hull panels is also investigated. A series of QSI tests are conducted in accordance with ASTM D7766 [3] standard test method to compare and determine the level of agreement between the force–displacement histories obtained from the experimental tests and the FE model.

2. Description and fabrication of hull panels

Marine composite sandwich hull panels are fabricated in accordance with the design presented by De Marco Muscat–Fenech et al. (2013) [4]. The CE category C certifiable hull panels were designed in accordance with the small craft standard BS EN ISO 12215–5:2008 [5] for vessels of a hull length less than 9m. DIVINYCELL® H100 closed–cell cross–linked PVC foam–core is sandwiched between two identical skins. The composite skins consist of chopped strand mat (CSM) and/or woven–roving (w) E–glass fibre, as listed in Table 1, embedded in a matrix of POLYLITE® 440–M850 orthophthalic polyester resin.

Table 1: Description of hull panels including lay–up stacking sequence of respective skins.

Panel Name	Core Thickness (mm)	Skin Lay–Up Stacking Sequence	Skin Thickness (mm)
A	10	450CSM, 450CSM	1.05
B	10	450CSM, 300CSM	0.77
C	15	300CSM, 450CSM, 400w, 450CSM	1.56
D	15	450CSM, 450CSM, 600w, 450CSM, 450CSM	2.02

The skins are hand laid–up and co–cured with the foam–core under a vacuum pressure of 0.5 bars for 6 hours by using the vacuum bagging fabrication process. Co–curing is the process whereby the hand laid–up skins are cured coherently with the foam–core, such that no adhesive is required to bond the skins to the core. The panels are fabricated in a mean relative humidity of (58.6±2.63)% and a mean ambient temperature of (16.6±0.61)^{o}C. Panels to be subjected to QSI conditions in a rigidly–backed configuration (procedure A of ASTM D7766 [3]) are cut in dimensions of 75mm by 75mm; panels to be tested in a simply–supported configuration (procedure B of ASTM D7766 [3]) are cut in dimensions of 200mm by 200mm by using a water–lubricated diamond cutter as specified in ASTM D7766 [3]. The fibre mass and volume fractions of the composite skins are calculated by measuring the mass of all constituent materials prior to the lay–up process and the final mass of the cured sandwich panels. The mean mass and volume fibre fractions for the panels being used in the current investigation are 48.5% (±2.59%) and 28.9% (±1.54%) respectively. The composite skins were fully characterised by De Marco Muscat–Fenech et al. (2013) [4] in accordance with appropriate ASTM standards. In this investigation, the out–of–plane behaviour of the composite skins is conservatively approximated to be dominated by the material properties of the matrix material.

3. Simulation of QSI event

The QSI event is simulated using the FE method. An FE model simulating the QSI response of hull panel A in a simply–supported configuration due to a hemispherical indentor serves as the basic model in this investigation. The thickness of the core and skins, the material properties of the skins and the boundary condition configuration of the basic model are changed to investigate the QSI response of the hull panels listed in Table 1 due to simply–supported and rigidly–backed configurations, whilst assessing the validity of the basic FE model to simulate the QSI response of other hull panels and other boundary condition configurations.

The composite skins and the foam–core can be individually geometrically represented by three–dimensional (3–D) cuboids, as shown in Fig. 1(a). In Fig. 1(a), the point of origin of the Cartesian coordinate system is located mid–way through the thickness and across the width of the hull panel. Symmetry boundary conditions are applied to nodes located on planes x = 0 and y = 0 due to planar geometrical symmetry, material property symmetry and loading symmetry. The FE model is shown in Fig. 1(b). The geometrical model consists also of a 12.7mm diameter hemispherical indentor and a support fixture with a 127mm diameter central opening for the simply–supported configuration. For the rigidly–backed configuration, all nodes located at the bottom face of the lower skin are constrained from moving in the z–direction. The composite skins are discretised by 3–D 8–node structural solid–shell elements (SOLSH190) in ANSYS Mechanical v15.0, which are suited for simulating thin to moderately thick structures [6]. The continuum solid element topology of SOLSH190 also facilitates connectivity with other adjacent solid elements, namely SOLID185, used to discretise the foam–core. The FE model consists of 10 elements through the thickness of the core and 2 elements through the thickness of each skin, resulting in a total of 12600 elements. The FE model yields a solution within 1.5 hours by using an i5 3.1GHz core, 8GB RAM machine.

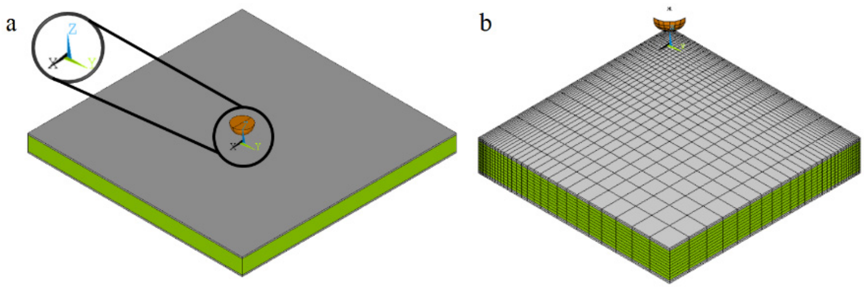

Fig. 1: (a) actual full 3–D geometrical model and magnified coordinate system; (b) modelled geometry in FE model.

The composite laminate skins are modelled as a single–layered homogeneous structure with equivalent material properties on the macroscopic scale. The Young's modulus, shear modulus, Poisson's ratio, and ultimate compressive, tensile and shear strengths of the skins of each panel are obtained from FACTS Laminate Property Calculator [4]. Both CSM and woven–roving sheets of E–glass fibre can be assumed to be transversely–isotropic, i.e. characterised by equal material properties in the two in–plane mutually perpendicular directions and different from those in the out–of–plane direction. In essence, a transversely–isotropic linear–elastic material model is used to simulate the material behaviour of the skins being used in the current investigation up to the initiation of damage. An instant stiffness degradation material model is then employed to simulate the degradation of the material properties of failed regions in the upper skin. A modified version of the stress–based failure criteria proposed by Hou et al. (2000) [7], as presented by Ivañez et al. (2010) [8] for transversely–isotropic composite laminates, is used to predict the occurrence of fibre failure in the in–plane directions and delamination in the out–of–plane direction of the upper skin. Matrix cracking and matrix crushing are not accounted for in the present FE model since the material behaviour of the skins in the two in–plane mutually perpendicular directions is dominated by the material properties of the fibre. The initiation of damage is instantly followed by a reduction in the material properties of failed elements. A degradation factor (DF) is employed accordingly to represent the reduction in the material properties. In case of fibre failure, all material properties are degraded, whereas for delamination only the out–of–plane material properties are degraded. A DF of 0.5 is found to provide correct results for simply–supported panel A and is taken to be the default DF in the current investigation. This DF was also used by Kärger et al. (2008) [9]. Fig. 2 shows the evolution of fibre failure and delamination in the upper skin.

The elastic–plastic material behaviour of the PVC foam–core is simulated by a linear best–fit approximation of GAZT yield surface [10]. GAZT yield surface is defined in terms of the deviatoric stress, the mean stress and the uniaxial yield stress of the polymeric foam material, whereby the mean stress varies quadratically with the deviatoric stress. The linear approximation is implemented through the built–in linear Drucker–Prager material model in ANSYS Mechanical v15.0, which also defines the yield surface in terms of the deviatoric, mean and uniaxial yield stresses.

In general, the force–displacement history of a foam–filled composite sandwich panel subjected to QSI conditions by a hemispherical indentor can be divided into three phases; an initial phase characterised by the elastic behaviour of the skins and the core (phase 1), the second phase dominated by interlaminar and intralaminar damage in the skins and elastic–plastic collapse mechanisms in the foam–core (phase 2), and a third stage controlled by the fracture of the foam–core and the puncturing of the upper skin (phase 3). A maximum strain criterion is used to detect complete failure of particular regions in the foam–core. This maximum total mechanical strain is taken to be 27%. Failed elements are taken to negligibly contribute towards the global stiffness of the hull panel by deactivating them. The solution is unable to converge for an indentation displacement greater than that corresponding to the maximum indentation contact force in the experimental force–displacement history. At this point, some elements in the modelled foam–core experience severe deformation and distortion indicating the occurrence of fracture in the core. Hence, the inclusion of fracture mechanics or the incorporation of a continuum damage mechanics material model through user material sub–routine (USERMAT) in ANSYS Mechanical v15.0 is required to simulate the third phase. Simulation of the third phase of the force–displacement history is undergoing present analysis and is beyond the scope of this work.

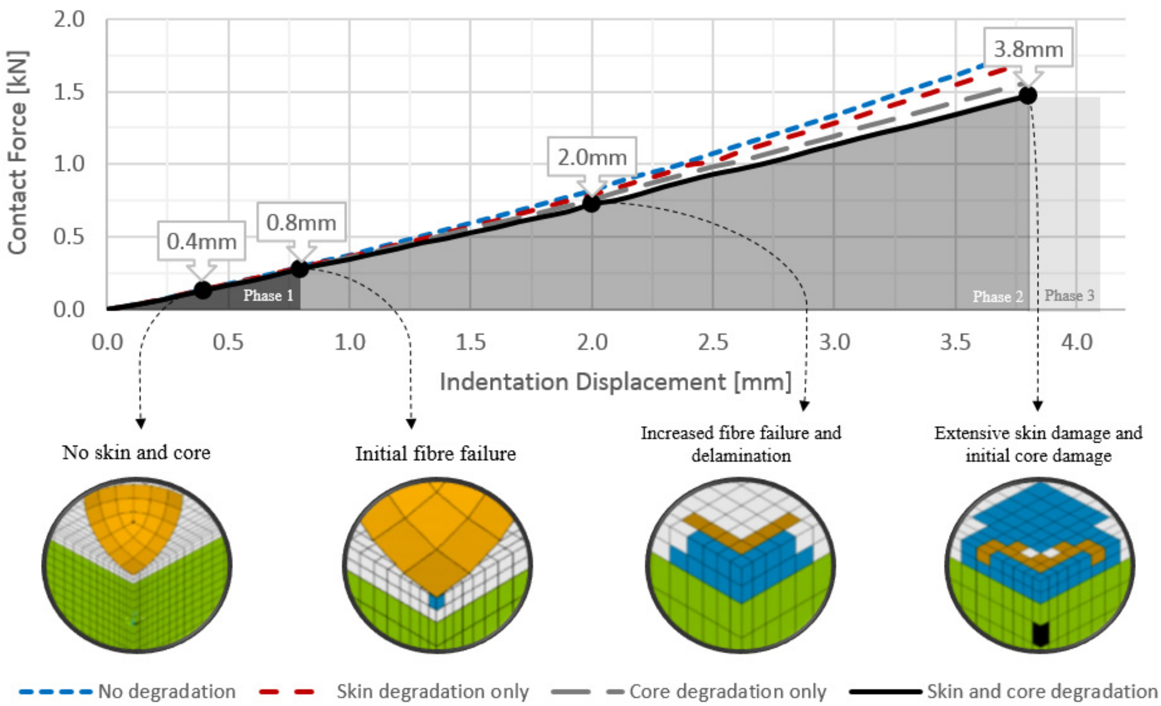

Fig. 2: Influence of skin and core degradation on force–displacement history (■ – undamaged skin, ■ – fibre failure, ■ – delamination, ■ – undamaged core, ■ – core complete failure).

Mesh studies and parametric studies are conducted to confirm that the force–displacement history obtained from the FE model is not influenced by the mesh density and options used to set–up the FE model to simulate the indentor–panel and panel–support interactions. Appropriate mesh density ensures the efficient use of computer resources.

4. Validation of finite element model

QSI tests are conducted in accordance with procedures A and B of ASTM D7766 [3], which are intended for measuring the damage resistance of composite sandwich constructions subjected to quasi–static indentation conditions in a rigidly–backed and a simply–supported configuration respectively. The mean force–displacement history as recorded from the QSI tests conducted on panels A, B, C and D is used to validate the simulated response determined from the respective FE models. A (47±1)g, (12.7±0.01)mm diameter hemispherical alloy steel (60–62 HRC hardened surface) indentor is used to indent the hull panels. The experimental setup is shown in Fig. 3, whereby the panel is rested on the fixture with a (127±0.1)mm diameter central opening for the simply–support configuration and on a solid support fixture for the rigidly–backed configuration.

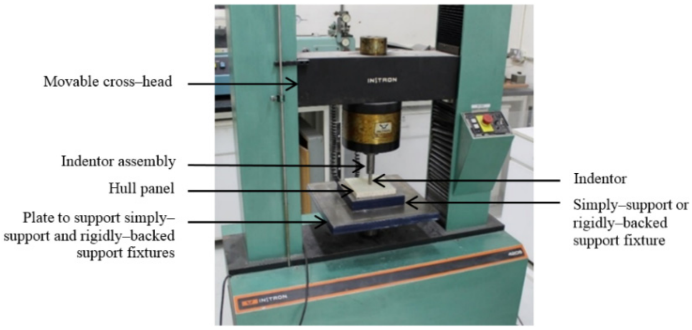

Fig. 3: Quasi–static impact test apparatus to simulate QSI conditions on hull panels.

The hull panels are indented at a controlled constant displacement rate of 1.25mm/min, such that the peak force in the force–displacement history is achieved between 1 to 10 minutes after the establishment of initial contact between the indentor and the panel, as specified in ASTM D6264 [11]. The force–displacement histories are measured using an Instron® 4206–006 universal testing machine. The indentation continues up to an indentation displacement of approximately 50% to 80% total hull panel thickness. The same test is repeated for a minimum of 5 times. The QSI tests are conducted at a mean ambient pressure of (75.904±0.6532)mmHg and a mean ambient temperature of (18.9±0.81)^{o}C.

5. Results

Although QSI tests are conducted up to an indentation displacement of approximately 50% to 80% total hull panel thickness, the basic FE model is validated by comparing the simulated force–displacement history (consisting of phase 1 and phase 2, as shown in Fig. 2) with the experimental force–displacement history for the same range of indentation displacement. The validity of the basic FE model set–up in this investigation to simulate the QSI response of hull panel A, subjected to a hemispherical indentor in a simply–supported configuration, is confirmed in Fig. 4(a). The force–displacement history obtained from the FE model falls within the 99% confidence interval of the mean force–displacement history obtained from the QSI experimental tests. A plot of the energy absorbed by hull panel A due to a hemispherical indentor is also shown in Fig. 4(a). The experimental energy absorbed is calculated by determining the area under the experimental force–displacement history curve by using the trapezoidal rule of integration, whereas that obtained from the FE model is the total mechanical strain energy computed by the model.

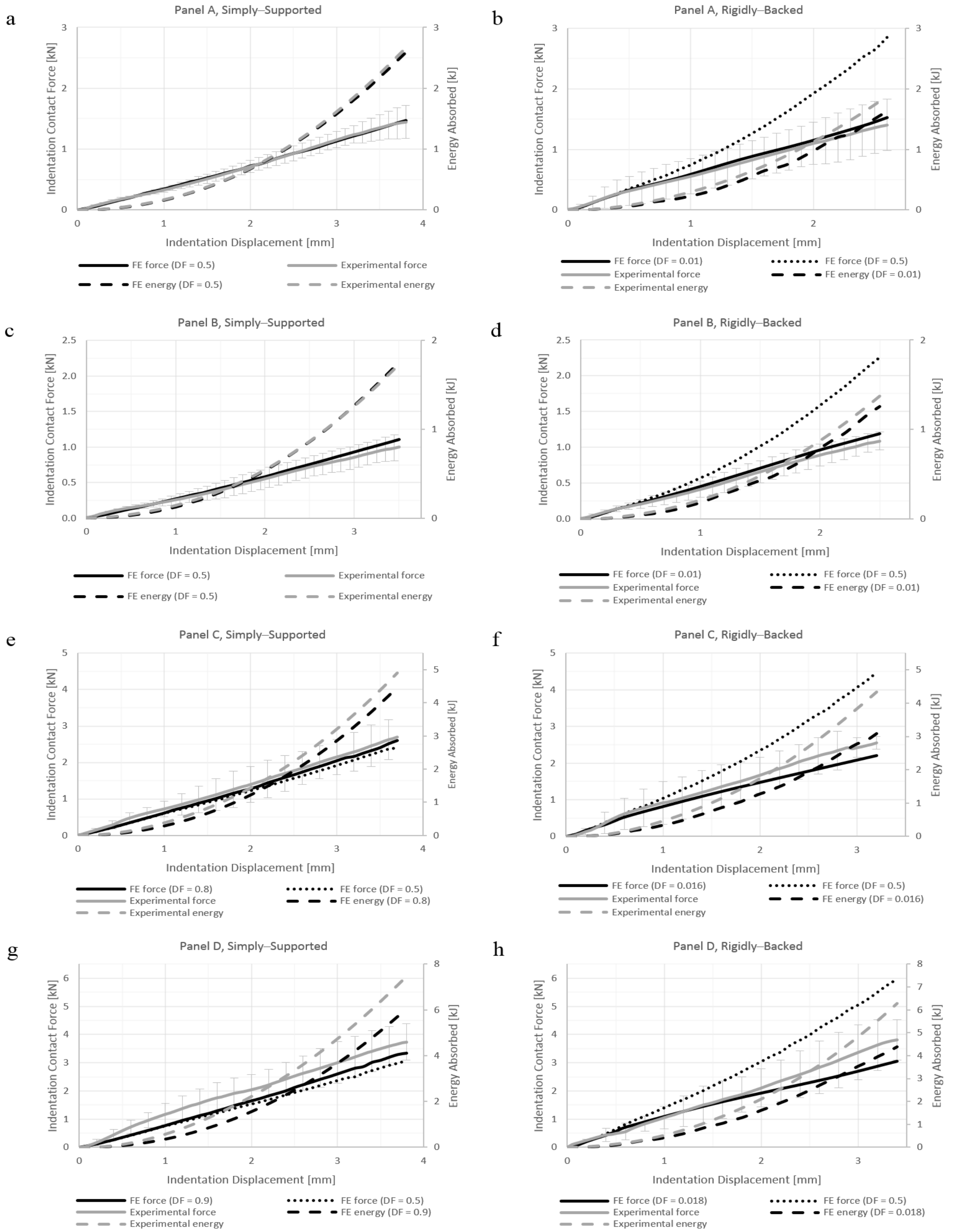

Fig. 4: Force–displacement histories (a) panel A, simply–supported; (b) panel A, rigidly–backed; (c) panel B, simply–supported; (d) panel B, rigidly–backed; (e) panel C, simply–supported; (f) panel C, rigidly–backed; (g) panel D, simply–supported; (h) panel D, rigidly–backed.

The FE model is capable of simulating the QSI response and to predict the force–displacement history of hull panels B, C and D subjected to a hemispherical indentor in a simply–supported configuration, as shown in Fig. 4(c), Fig. 4(e) and Fig. 4(g). The force–displacement histories obtained from the FE model for the other panels also fall within the 99% confidence interval of the experimental data. The use of a DF of 0.5 yields an average percentage error between corresponding FE results and experimental data of 8%, 15% and 27% for panels B, C and D respectively. Whilst the skins of panels A and B consist of only CSM sheets of E–glass fibres, those of panels C and D consist of a combination of CSM and woven–roving sheets of E–glass fibre. Hence, it is concluded that the relatively greater percentage errors for panels C and D, when compared to those of panels A and B, is due to the presence of the woven–roving fibre sheets. De Marco Muscat–Fenech et al. (2014) [12] also noted that the presence of woven–roving sheets of E–glass fibre improves the impact resistance of the hull panels subjected to QSI. By noting that the average percentage error increases by 12% from panel C to panel D, it can be concluded that the greater the aerial density of the woven–roving fibre sheet, the more improved the impact resistance of the hull panel is. It is found that by employing a DF of 0.8 and 0.9 in the instant stiffness degradation material model of panels C and D respectively, the level of agreement between the force–displacement histories obtained from the respective FE models and experimental tests is improved, as shown in Fig. 4(e) and Fig. 4(g). In fact, the average percentage error is reduced by 4% for panel C and 5% for panel D.

The indentation contact force in the force–displacement history of hull panels A, B, C and D subjected to a 12.7mm hemispherical indentor in a rigidly–backed configuration, as determined from the FE model, turned out to be overestimated with respect to the experimental data, as shown in Fig. 4(b), Fig. 4(d), Fig. 4(f) and Fig. 4(h). The overestimated results are attributed to energy dissipation mechanisms, such as the propagation of matrix cracking, in the upper skin, which are unaccounted for in the FE model. The application of vacuum pressure on the hull panels during the fabrication process decreases the final amount of matrix material present in the composite skins. In essence, the volume fraction of the brittle E–glass fibre is increased in the skins of hull panels co–cured by using the vacuum bagging process when compared to those cured under atmospheric pressure. This increases the overall brittleness of the skins. Dassios (2007) [13] noted that propagation of matrix cracks creates a deficiency of matrix material around the fibre such that transfer of stress between the affected fibre and surrounding fibres would be impossible, thereby resulting in fibre pull–out. The presence of fibre pull–out is confirmed by the visible whitened area around the permanent indentation, as shown in Fig. 5, which is associated with delamination and fibre pull–out by De Marco Muscat–Fenech et al. [12]. It is found that the DF employed in the instant stiffness degradation material models for the simply–supported hull panels should be reduced by a factor of 50 for the rigidly–backed hull panels in order to account for fibre pull–out due to matrix cracking. In essence, a DF of 0.01 is used for panels A and B, a DF of 0.016 is used for panel C and a DF of 0.018 is used for panel D. The average percentage error is reduced from 47% to 6% for panel A; from 28% to 8% for panel B; from 33% to 13% for panel C; and from 39% to 14% for panel D.

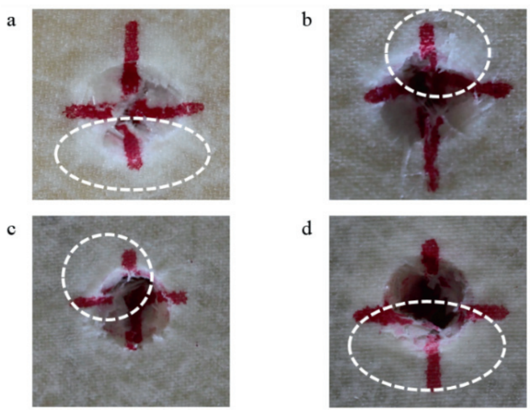

Fig. 5: Visible (encircled) fibre pull–out and delamination in upper skin of rigidly–backed (a) panel A; (b) panel B; (c) panel C; (d) panel D.

6. Conclusions

Conclusions drawn from extensive FE modelling and experimental testing of QSI events involving indentation collisions with certifiable marine grade hull panels are:

- The FE model consisting of an instant stiffness degradation material model and elastic–plastic collapsing of the foam described by a linear best–fit approximation of GAZT yield surface is capable of simulating the QSI response due to a 12.7mm hemispherical indentor.
- A DF of 0.5 yields correct results for hull panel A and B, which consist of only CSM composite skins, subjected to the hemispherical indentor in a simply–supported configuration.
- The inclusion of a 400g/m^2 and 600g/m^2 plain woven–roving sheet of E–glass fibre in the composite skins increases the DF to 0.8 and 0.9 for simply–supported panels C and D respectively.
- Energy dissipated by fibre pull–out due to the propagation of matrix cracking, as observed in rigidly–backed panels, reduces the amount of strain energy stored in the hull panels. A DF of 0.01 for panels A and B; a DF of 0.016 for panel C; and a DF of 0.018 for panel D provide valid results for rigidly–backed hull panels.

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